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A REVIEW OF THE EFFECTS OF WEIGHTLESSNESS ON SELECTED HUMAN MOTIONS AND SENSATIONS

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FOREWORD

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ABSTRACT

The motions of the weightless free-floating worker are discussed in terms of an operator performing maintenance and supply functions between, upon, and within space vehicles. A postural coordinate system is used as a basic reference and current USAF studies concerned with rotating and translating the system are reviewed. Study techniques include physical analyses of the motions, inflight validation of the analyses and mathematical projections of probable orbital motions. Sensations to these motions and the ability to handle inertial objects is also discussed.

The motion freedom of the unencumbered surface-free worker revealed many restraint requirements and such designs as lifelines, adhesive footgear and self-maneuvering units are introduced to limit and control his motions. These designs are being used to determine human factor criteria for space hardware and to suggest crew selection and training procedures.

The effects of transient weightlessness on sensory, psychomotor, and motor functions have revealed minor effects; however, the perception of the postural vertical and the response of the circulatory system to the return of positive gravity are considered as pertinent problems.

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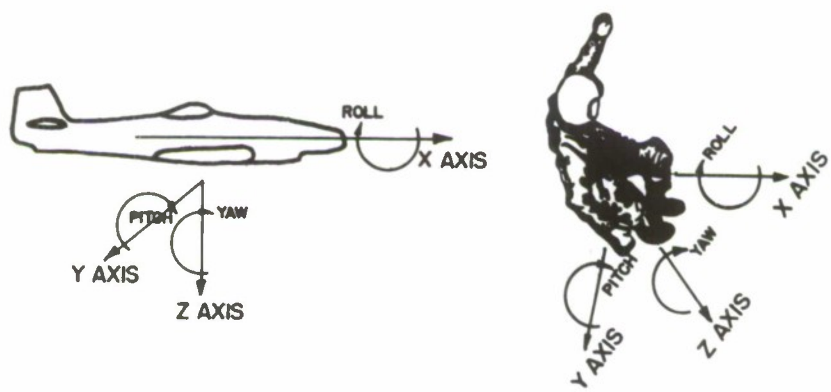
GLOSSARY

GLOSSARY OF SPECIAL TERMS USED IN THIS REPORT

SELF-ROTATION	body rotation resulting from body manipulations
CONTROLLED ROTATION	body rotation resulting from mass expenditure
SELF-MANEUVERING	body rotation and translation resulting from mass expenditure
TETHERING BEHAVIOR	body motions and flight paths influenced by safety-lines attached between weightless masses
SOARING	body flight paths resulting from single-impulse launches
FRACTIONAL GRAVITY	an acceleration field between 0 and +1 g, often referred to as partial g, subgravity, reduced, artificial and induced gravity
POSTURAL ORIENTATION	an attitude concept of 'feet are down, head is up' resulting from the worker's perception of himself rather than his surroundings as his frame of reference
POSTURAL CONTROL	a concept of controlling body rotations and translations by body manipulations

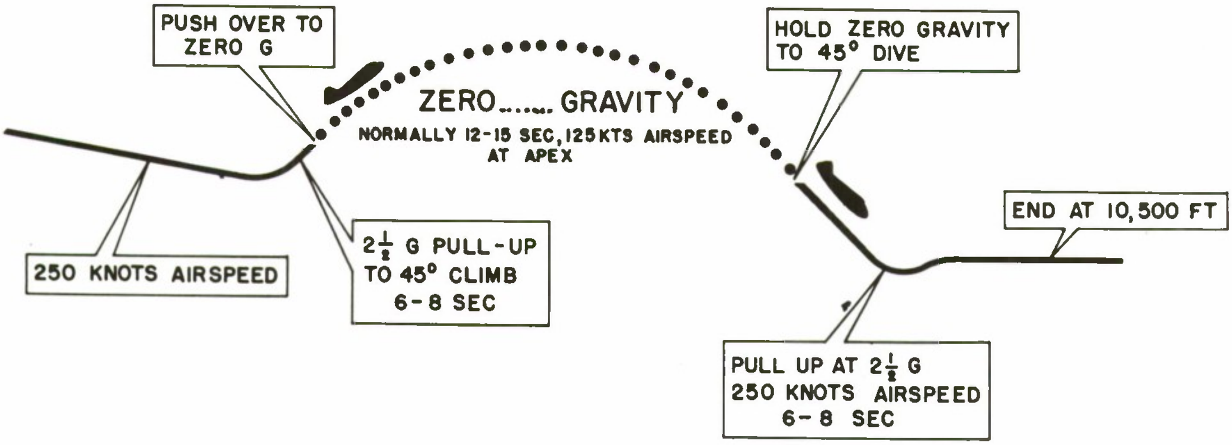
I. INTRODUCTION

In the world of space technology, where an instrument panel is called "a command center display console," it was inevitable that man himself would be redefined. And, in fact, in Los Angeles recently, two bio-engineers did it. Working out the mathematics of man's movements during weightlessness, they suggested that, for purposes of their equations, man "may be described as a non-symmetrical, fluid-filled sack of variable shape containing a large air bubble." The unlimited motion capability of this weightless blob, hereafter referred to as an orbital worker, has introduced new horizons of movement as well as dark avenues of motion danger for free-floating man in space. This paper reviews some of the advantages and problems of motion and sensory performance in the action-reaction environment of weightless man in the orbital situation. The motions of the weightless worker are discussed in terms of a man performing maintenance and supply functions between, upon, and within space vehicles.



The generally accepted NASA/USAF airplane axis system shown above was used to establish the motion coordinates for the free-floating worker. An upright figure was chosen because the vehicle and the driver are treated as a single system and the 'forward' (X axis) motion is comparable to the pilot's alignment in the aircraft.

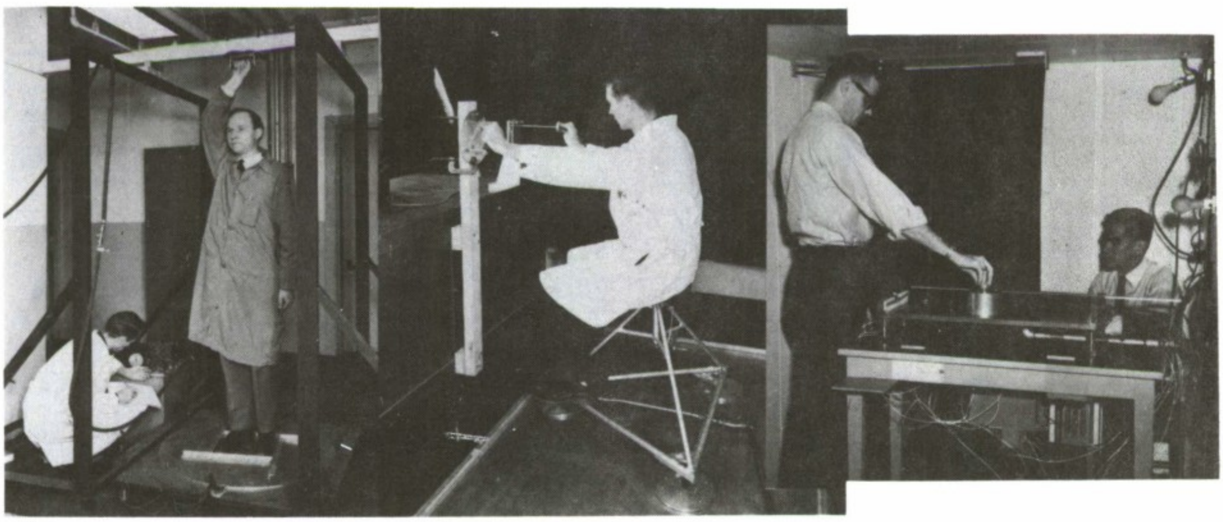
The research facilities used to study these motions included both ballistic and frictionless devices:



1. LARGE CABIN VOLUME AIRCRAFT flying 14 to 30 second weightless trajectories as shown above, are used to suspend subjects free from all surfaces and offer them freedom of motion (ref. 3).

2. FRICTIONLESS DEVICES or air bearing platforms are used to simulate the tractionless characteristic of weightlessness.

a. The ROTARY PLATFORM (below, left) is a circular disk, 36 inches in diameter, that is pivoted at its center. Compressed air is delivered through holes under the plate, thus supporting it on a "cushion" of air. The plate offers YAW rotational motion.



b. The "3-D" SCOOTER (center) is a tricycle-like device, supported on three 8-inch disks. Compressed air delivered through these disks supports the scooter on a cushion of air. The scooter moves over a smooth steel plate and offers X, Y, and yaw motions.

c. The FRICTIONLESS TABLE (above, right) is made of two metal plates fastened together to form a hollow chamber. The top plate is perforated with 260 holes, 1/64 inch in diameter. Air is delivered through a 1/2 inch hole in the bottom plate. This table is used to support different weights and has been used in studies of discrimination and positioning of mass.

II. BODY MOTIONS

A. <u>NO MOTION (relaxed posture)</u> - It may be appropriate to first consider a motionless man and his probable configuration before his motions complicate the succeeding problems. Experience of free-floating personnel indicated that there was a tendency for the limbs to assume new positions during weightlessness. Seated observers have commented that their feet and arms tended to rise off the floor and the arm rests, respectively, and that they must consciously maintain their extremities in contact with supporting surfaces (ref. 7). Free-floating subjects have commented that, when they relax, they tend to assume an ATTITUDE RESEMBLING THE SEATED POSITION.

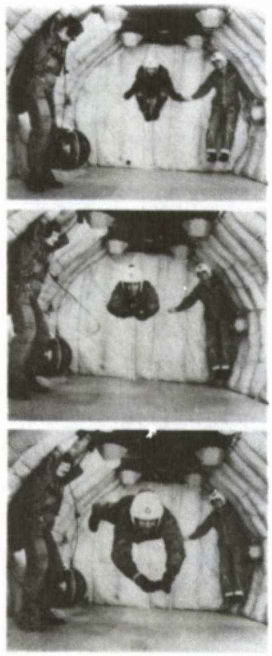
(The figure to the left of the drawings includes the coordinates of the motions being discussed, in this case, an absence of motions)

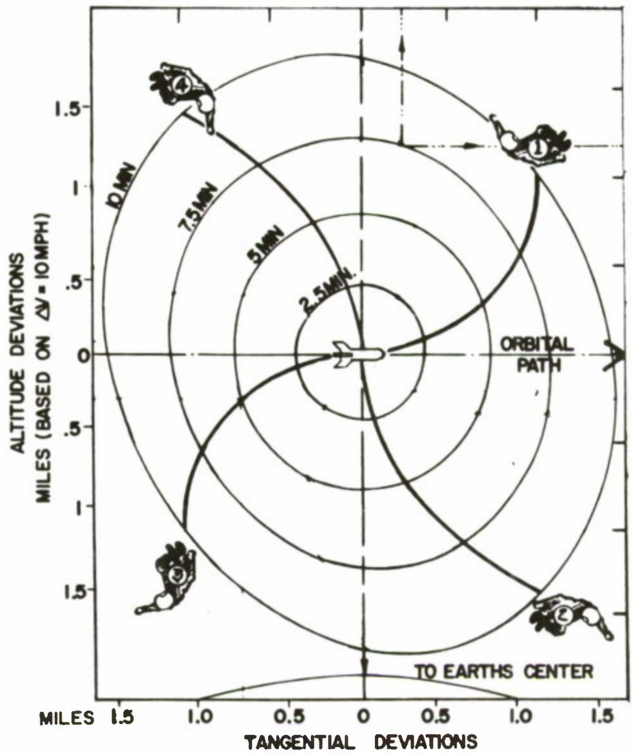
The figure on the right represents a theoretical posture derived from the assumption that individual body segments will find positions of equilibrium near the midpoints of the ranges of movement of their joints. If this speculative body posture is validated, it may dictate seat and couch configurations as well as placement of controls in the crew station.

B. LINEAR MOTIONS

(1) SOARING between vehicles

The worker can, with low thrust levels, SOAR within a large vehicle or between orbiting vehicles. For SELF-PROPULSION from a surface, subjects will generally use the legs because of their ability to propel the body with the greatest force applied for the longest time.



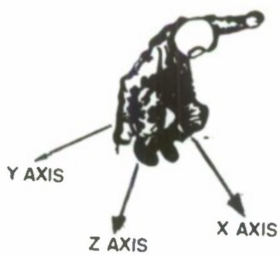


During zero g aircraft flight, subjects (pushing off with legs) attained velocities of approximately 10 mph. All subjects suffered slow, undamped rotations because of their inability to precisely program thrust through their center of mass during launch. Once free of the bulkhead, the subjects had NO POSITION CONTROL and POOR ATTITUDE CONTROL as their trajectory was determined solely by their launch.

Orbital projections of these single impulse launches were computed for man in space and show his flight path relative to his departed vehicle (right chart). A forward launch will position the worker over 1 mile ahead and 1 mile above the vehicle after 10 minutes of soar. After one earth orbit of about 90 minutes, the worker would find himself 47 miles directly behind his ship. The complexities of soaring can be appreciated when one notes that an earth directed soar will find the worker 11 miles in front of the vehicle after 45 minutes and arriving back at the ship from ABOVE after 90 minutes. These idealistic, single-impulse trajectories show the potential trajectories for accomplishing short-orbital transfers between vehicles (ref. 10) and the awesome results of an inadvertent or purposeful launch.

(2) SOARING within vehicles

Workers will be able to soar within a large vehicle just as crew member now walk along walkways. Soaring will require a volume definition of soarway requirements and a determination of handhold configurations and placement. Handholds or handrails will serve as anchor points for personnel propelling themselves along either the X, Y, or Z axes. The space required is being established by soaring subjects within the test aircraft.



The adjustable bulkhead shown above is being used to establish the minimum area required for soarers to traverse a bulkhead or airlock hatch. As the area and volume requirements are established, operator techniques will be studied as 'shirtsleeve' and pressure suited subjects attempt to use actual bulkhead doors and handholds.

(3) <u>WALKING on a vehicle</u>

Our worker will probably use adhesive footgear to locomote on surfaces inside and outside of nonrotating vehicles. Without some restraining devices, the normal walking gait will propel the weightless worker from his surface. Several varieties of adhesive footgear have been developed to enable the walker to locomote.

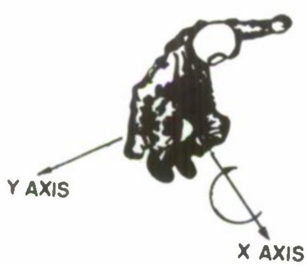
Shown above are permanent magnet sandals, electromagnetic shoes, and a subject walking with adhesive cloth (Velcro) material on an overhead panel.

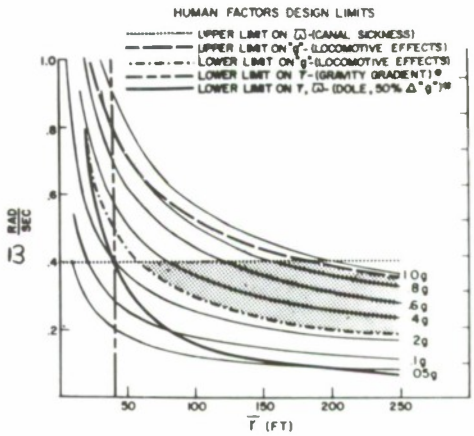
These special aids force an abnormal walking gait on the operator because, in the act of pulling his foot loose, he pulls his body toward the retracting foot and introduces a pronounced roll of the body. Also, starting and stopping introduces a pendulous pitch because of the worker's requirement for controlling his entire accelerating body mass by ankle muscle without the aid of a body-to-surface directed weight force.

A FOOT-IS-DOWN concept of orientation was noted by non-rotating subjects, regardless of their position within the aircraft, and floors and ceilings were perceived as "a collection of surfaces." The concept of POSTURAL ORIENTATION wherein the operator perceives HIMSELF rather than his ENVIRONMENT, as the focal reference for spatial orientation, was derived from this foot-down orientation, due, apparently, to a lack of stimulation of the inner ear balance mechanism accompanied by the continued stimulation of deep muscle recepters. The single-floor concept of earth man may be an unnecessary weight penalty for space vehicle layout and the display of attitude information to the pilot may be MAN rather than EARTH or vehicle oriented (ref. 16).

(4) WALKING within a rotating vehicle

Much has been written about the advantages of living in a spinning space station. The concept of creating artificial gravity by rotating a space vehicle introduces the interacting conditions of fractional gravity (between 1 and 0 g) and Coriolis effects caused by the worker movement on a moving surface.





The chart outlines the design limits for a rotating space station. The shaded area represents the desirable rotation speeds and vehicle radii (ref. 9).

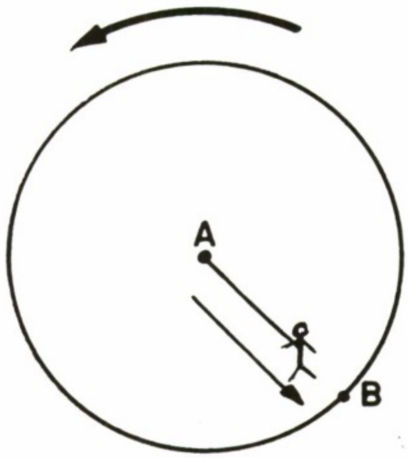
The lower limit of induced g that can be used for successful walking was established near .2 g, and an upper practical limit was established near 1 g. In both of these, the value has been set so that by walking against or with the rotation of the vehicle, the +1 and +.2 g limits are not violated by the crew member. An upper limit of .4 rad/sec was placed on angular velocity in order to minimize the Coriolis effects leading to canal sickness.

Engineering considerations such as structural loads and material stresses have described the upper limit on radius of rotation, and a "gravity gradient" or the difference in g between the head and foot of a standing person, has been established at .5 g, therefore establishing a lower limit on radius of approximately 40 feet.

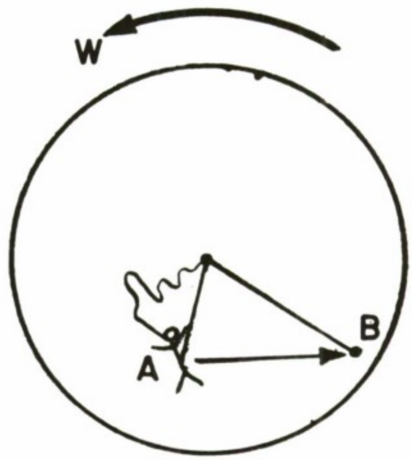
Studies of operator limits within radial spokes of a rotating station are now being conducted.

(5) LOCOMOTING on a rotating vehicle

Our worker will find some astonishing motions at his disposal when he performs on the outside of a rotating space station. He can be tethered (tied) with a lifeline to the spin axis (center of rotation) of the vehicle to prevent him from being thrown off into space and this point of attachment may enable him to reach any position on the vehicle (ref. 6).



RADIAL MOTION
"A" TO "B"



ANGULAR MOTION
"A" TO "B"

He can move directly toward or away from the spin axis (above, center) by properly using his lifeline. He can achieve this radial displacement by merely VARYING THE LENGTH OF A TAUT LINE. The worker may accomplish this task regardless of whether or not his feet are in contact with the surface of the station. If his feet remain in contact with the surface, his motion will be linear and if he removes his feet, his motion will be curvilinear.

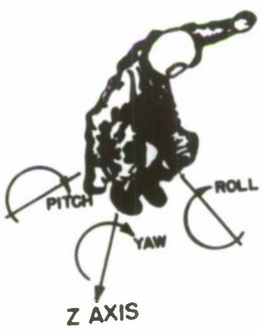
Motion to achieve angular displacement (above, right) can be achieved by KEEPING THE LINE LOOSE AND REMOVING BODY CONTACT from the surface of the station. His motion will be linear, and will be the result of tangential velocity from the last point of contact. All that is necessary to stop angular displacement is to pull the tether taut. The man can then adjust the tether length to stop at a desired point.

Problems involved in this type of locomotion will include keeping a stable attitude, gravity effects induced by rotation, developing a usable tether line, motion due to a varible tether angle with the station surface, canal sickness, and effects of the linear motion of the station itself.

C. ROTATIONAL MOTIONS

(1) TETHERED to a vehicle

For performing inspection and maintenance functions on the outside of a vehicle, the worker may use a man-to-surface tether apparatus. For a task involving limited movement in the immediate vicinity of one portion of the outside surface of the space craft, a spring loaded tie-down technique is being studied to allow yaw.

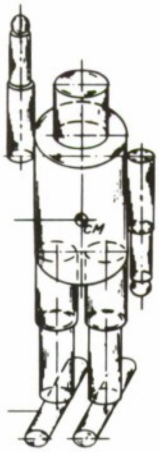


The subject wears a belt freely rotating within another belt and this system is suspended by lines attached between the surface and inertia reels on the belt. With equal tension inall lines, the only force on the man will be toward the space craft (or along Z when standing), which he will oppose by standing or kneeling on the surface (ref.14).

Motion away from the surface along Z would be limited by the standing height of the man. Motion in a direction parallel to the surface (X or Y) is limited since any displacement away from the zero point causes unequal tension in the lines and this net force has to be overcome by the man through friction with the surface and the torque overcome by spreading the feet. The worker may vary his alignment to the surface, for example a prone position can be assumed by using one stomach-to-surface line and still retain yaw freedom.

(2) SELF-ROTATION

The worker cannot linearly move himself when between vehicles, however, he can turn himself by carefully moving his arms and legs in predetermined motions. Nine maneuvers (ref. 7) have been proposed for achieving self-rotations through body manipulations by calculating rotations of stick models shown below (center).



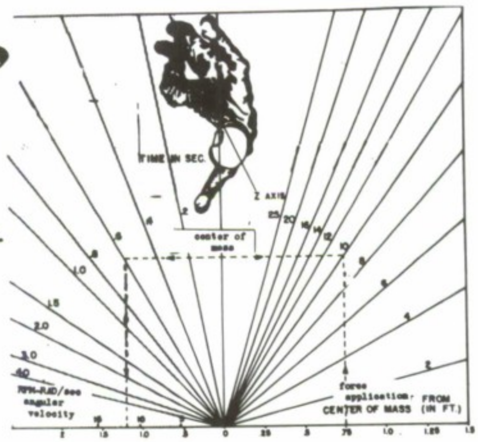
The linear and angular momentums of the static worker are zero. The body is flexible, however, and capable of generating internal forces and moments. The worker can rotate his arms at the shoulder and his arms will have an angular momentum; however the rest of the body will rotate in the OPPOSITE direction because the total body angular momentum must remain at zero. When he stops rotating his arms, his body rotation stops. By adding mass to his hands, he can increase his body rotation velocity. If the worker were spinning, he might be able to rotate his arms to stop the spin, however, he would again spin as soon as his arm rotation stopped.

The rotations are inefficient because of IMPURE ROTATIONS, (coupling motions about other axes) and demand MUCH ENERGY EXPENDITURE for small amounts of body rotation. Training in these self-rotation maneuvers, however, will probably be conducted for space candidates who must face the probabilities of hardware failure and emergency rotation requirements.

A dynamic (conservation of linear and angular momentum) model of the flexible weightless man is needed to bridge the gap between anthropometric data and the equations of motion needed for engineering design. Whitsett (ref. 18) is attempting to approximate the mass distribution, center of mass, moments of inertia and degrees of freedom of a human being. The model could be used to study problems of stability, axes of rotation (which are unlimited with a flexible form), body responses and tumble behavior. One method being used to validate the model is to initially spin a subject about one axis and measure the magnitude and torque a man can exert from the resulting reaction of a change in posture during a spin. The tumbling subject can reduce his rpm about Z from 14 to 5 rpm (a ratio of 2.5 to 1) in .4 seconds after assuming a spread-eagled posture.

(3) CONTROLLED ROTATION

For more intricate tasks to be performed between vehicles, the worker may require a back-packed stable platform. A device to offer man tumble recovery, controlled rotation, and inherent stability properties is currently under study.



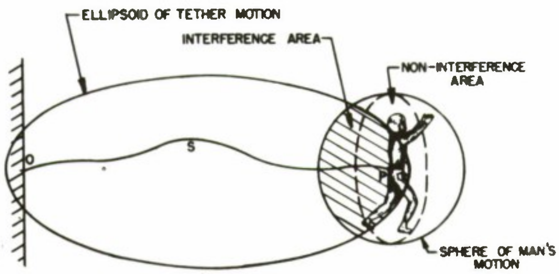
By adding two gyroscopic elements to the worker shown above (right), stability can be obtained about three axes since a gyro element has inherent stability about two axes. Purposeful rotation can be achieved by torqueing a wheel axis and thereby precessing (rotating) the entire system. System design for this exploratory concept includes a 5 rpm rotation rate for a 160# worker and a coupling effect (rotation about other axes) of only two degrees per revolution. Prime human factor goals are a determination of desirable rates of rotation, optimum control properties and tumble recovery techniques.

X movement might be added to these motions by the worker traversing a lifeline suspension between vehicles or by soaring over short distances. The chart (above, center) plots the forces needed to turn a rigid worker about Z (note that a 10# force applied .75 feet from his center of mass, for .6 seconds will turn the worker at 13 rpm).

D. LINEAR AND ROTATIONAL MOTIONS

(1) TETHERED between vehicles

The worker may use a lifeline to return to a vehicle and to prevent inadvertent tumbling. The soaring paths have shown the need for safety lines which will restrict the workers' motion freedom during soaring and cause changed flight paths when the line becomes taut.

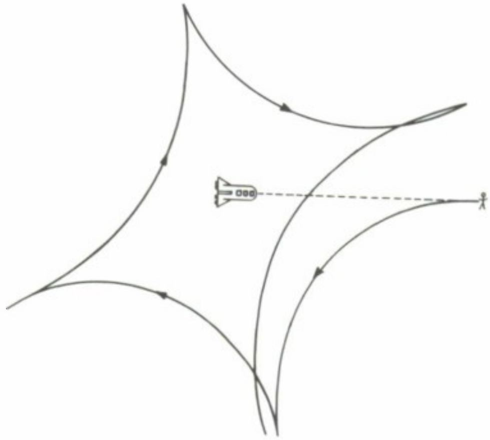


With slack in the line (above, right), the line can move within an ellipsoid and the man has unrestricted movement except where the man's rotational motion (shown as a sphere), overlaps the ellipsoid in a zone of interference between the line and the man. The worker can individually retain roll, pitch, or yaw freedom with minimum line entanglement by MOVING his point of attachment to his desired axis of rotation (ref. 14).

Motion along a lifeline strung within or between vehicles will offer the worker guided trajectories. Subjects grasped a 3" ring (below, right) and soared along a stretched nylon cord after using hand or foot launches.

Position control was easily maintained, however, attitude behavior was erratic. (The author has thrown a ball above the subject in order to judge Coriolis effects on soaring subjects in a rotating aircraft; forward moving masses tend to move toward the ceiling). Deceleration programming can probably be handled with a friction clutch on the ring and a hands-free capability accomplished by attaching the ring to the soarer's shoulder.

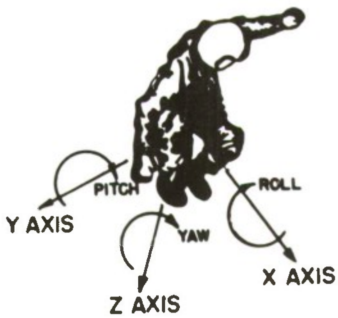
Potential problems with this motion may include motion of the lifeline anchor points (a taut line will move two attached masses toward each other) and line whiplash, however, this activity within a large vehicle should be relatively free of hazards.



The movement of the worker tethered immediately ahead of the vehicle's path reveals the unusual orbital motions which the worker must face in space (above, right). If he pulled on the line and it remained slack, he would immediately lose altitude because of his decreased orbital velocity and bounce toward the vehicle when his line tightened. He would continue arcing (and tumbling at the end of the line) as shown in the figure until he applied other forces to the line. These trajectories reveal the need for determining the desirable damping characteristics of the lifeline (a rigid line may continuously 'bounce' the operator) and introduce new flight paths possible for the operator.

(2) SELF-MANEUVERING UNITS

The worker can assemble prefabricated units, tow supplies and even move vehicles with a propulsion unit offering rotation and translation motions. Several systems for controlling man in all motions are being developed.



A two-hand controlled, compressed air, self-maneuvering research unit developed by the Bell Aerosystems Co.(center) was developed for studying optimum nozzle placement and thrust requirements.

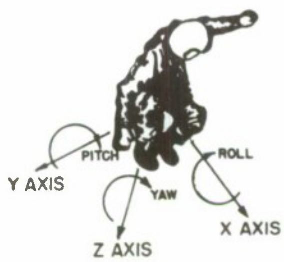
A space Self-Maneuvering Unit (right) was designed by the Chance-Vought Aviation Co., and is a self contained propulsion and life support system, weighing approximately 150 pounds, which straps to a pressure-suited man's back and provides him with the means to maneuver and perform useful work outside his space vehicle. The propulsion system is powered by either liquid Freon or hydrogen peroxide and consists of 10 fixed nozzles which bracket the man's center of mass and, together with 3 rate gyros and a digital logic circuit, provides the man with automatic stabilization. The unit is controlled by a controller located on the man's chest and can be operated one-handed by either the right or left hand. The hydrogen peroxide fueled Self-Maneuvering Unit will enable a man to travel to a work site 12,000 feet away from his parent vehicle, provide 1500 pound-seconds of impulse for maneuvering at the work site, and enable him to return. The life support equipment will sustain the man for 4 hours outside his vehicle.

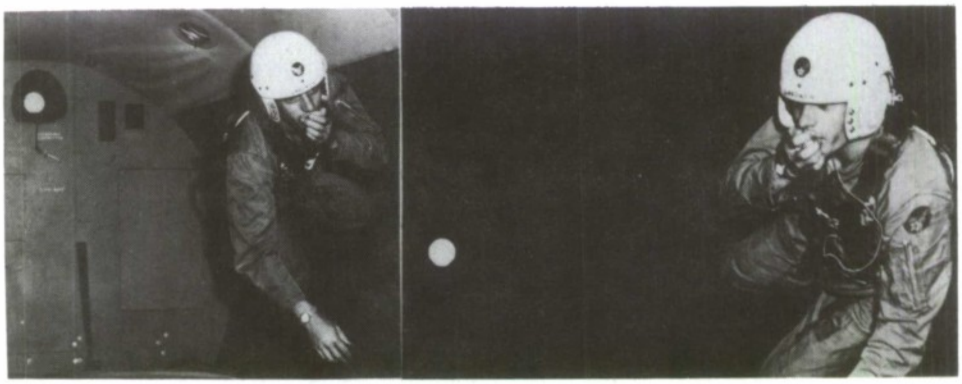
Severe limitations may be placed on the rates of the translatory motions because of CURVED flight paths and poor RATE OF CLOSURE information. The curved trajectories will produce confusing line-of-sight problems and dangerous closure rates will promote deceleration problems (ref. 15).

(3) MOTION SENSATIONS

The effectiveness of man as an operator depends upon his perceptual behavior (sensations) and well being as well as his motion performance. What sensations will our worker have when he departs his familiar surface and moves into the black void of space? A single study attempted to outline these SENSATIONS of the worker as he responded to his surface-free motions (ref. 17).

The NASA astronauts, deep-sea divers from the U. S. Navy New London Diving School, and USAF personnel verbally recorded their sensations as they free-floated in lighted and darkened cabin conditions in the aircraft (center and right). They accomplished linear and rotational motions such as walking, tumbling, soaring, and tethering tasks designed to free them from the cabin surfaces.





Some of their sensations were categorized as follows:

a. Exhilaration of Freedom from Surface - subjects who were not annoyed by motion sickness almost invariably smiled and laughed, appeared to enjoy their soaring and reported symptoms of euphoria and exhilaration.

b. Comfort of Tactualess Support (absence of skin pressures) - the comfort and ease of tactualess support was often reported.

c. Sensation of Falling - the sensation of falling is rarely experienced and fear and panic responses are infrequent.

d. Knowledge of Limb Position - the static positions of limbs are known; however, moving limbs may cause confusion, overreaching, and an oscillating center-of-mass.

e. Knowledge of Body Position - non-rotating subjects appear content with their concept of POSTURAL ORIENTATION of themselves rather than the vehicle as a frame of reference.

f. Knowledge of Rotation - subjects tended to underestimate their own rates of rotation and spinning maneuvers caused disorientation without dizziness.

g. Knowledge of Surface Location - knowledge of surface location was poor and knowledge of body-to-surface alignment was almost non-existent (dark condition).

h. Concern over Collision - Difficulty in Absorbing Inertia - concern with potential body injury during a surface collision was a dominant apprehension. The unawareness of an approaching surface and the inability to self-rotate and prepare for a landing were reported as major fears.

i. Illusions - the complex acceleration pattern of the maneuver induced real and apparent motions of the environment.

j. Sense of Heaviness after Maneuver - the frequent sensation of excessive body weight sometimes lasts hours after a flight of many maneuvers.

k. Decrease of Clothing Pressures - the first indication of fractional g was often a tactual response to decreased clothing pressures.

l. Motion Sickness - the majority of naive subjects showed various symptoms of motion sickness which was probably caused by the quick transition from + g to 0 g in the aircraft maneuver.

The experience of many observers in flight indicates that ORIENTATION is not a problem during short periods of weightlessness as long as visual and tactual references are available. The body of evidence to date strongly supports postural factors as being the primary ones for perceiving the postural vertical and exerting a very strong effect in the perception of the visual vertical (ref. 8). Pigg has found an average VISUAL ACUITY decrement equivalent to a 6% increase in visual angle of targets at threshold legibility; however, for ordinary purposes of vision this is not of practical significance (ref. 11). Tests of PSYCHOMOTOR PERFORMANCE have shown that a person firmly attached to his workplace (ref. 8) can carry out many psychomotor tasks with reasonable proficiency and that practice improves performance. If the problem of inadvertent tumbling can be avoided, it appears that a free-floating man could perform many tasks adequately. The physiological activity that has received the most attention is the CIRCULATORY SYSTEM (ref. 2). The greatest risk of circulatory failure may occur upon reentry to a high g field, after the muscles and circulatory system have become adjusted to the changed pressure relationships that are due to zero gravity. Graveline is currently exploring the use of pulsing tourniquets for maintaining proper circulation during weightlessness.

Long term orbital vehicles will be required to isolate true sensory responses from those responses measured under the extreme varying g conditions of a parabolic maneuver, however, no formidable sensory complications have yet been detected.

III. MATERIAL HANDLING MOTIONS

The orbital worker will be required to handle objects and equipment that are around him and the question arises, "How well will he be able to do this?" Using the frictionless devices to stimulate the tractionless aspect of the space environment, several studies were carried out to determine the effects of weightlessness on man's ability to discriminate and handle inertial objects.

A. DISCRIMINATION OF MASS

A laboratory study was conducted to compare man's ability to discriminate small differences in mass with his ability to discriminate small differences in weight (ref. 13). Four weight series were used, each consisting of a standard (1000, 3000, 5000, and 7000 grams) and nine comparison stimuli. Judgements for mass differences were made using the same weights on the frictionless

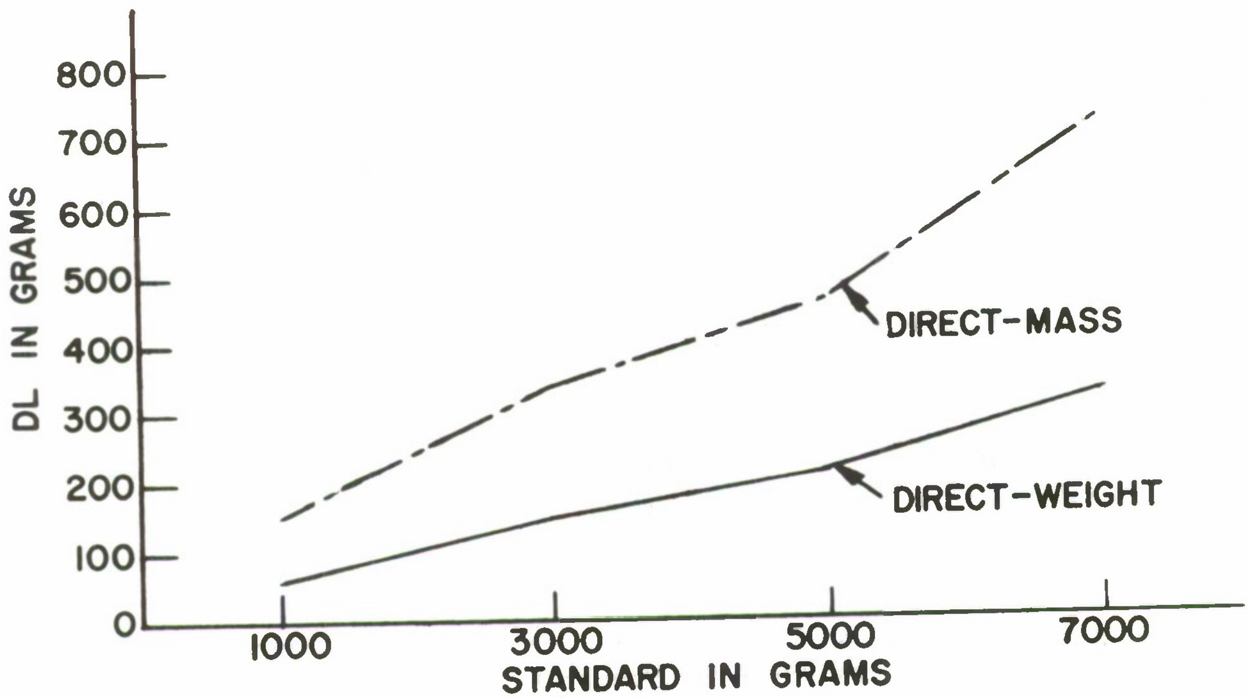
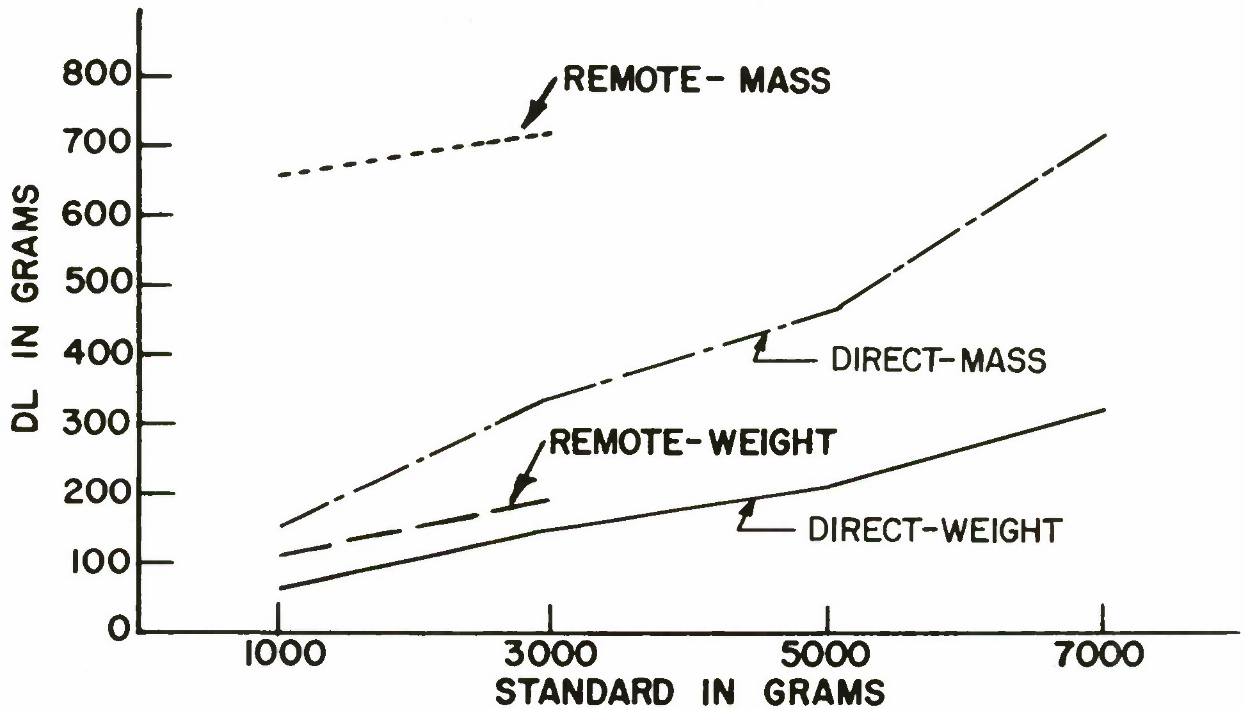


table. The results above showed that difference thresholds, i.e. the amount two stimuli must differ before it will be perceived as being different 50% of the time, were approximately TWICE AS LARGE FOR MASS AS FOR WEIGHT and also approximately proportional to the mass handled. It was also found that the difference ratio for mass was .10, that is, for two objects to be perceived as being different in mass, THEY MUST DIFFER BY 10%. This is also twice that for weight, the difference ratio for weight being .05.

B. DISCRIMINATION OF MASS (Remote)

Since the space environment is both hostile and hazardous, i.e. temperature, radiation, etc., it is anticipated that remote handling equipment will play a major role in space. A study was done, therefore, to determine man's ability to discriminate small differences in mass remotely (ref. 1). Two weight series consisting of a standard (1000 and 3000 grams) and eleven comparison stimuli were used. Judgments for mass were made using these two weights on the frictionless table. The difference thresholds obtained in this



study approximately DOUBLED THE DIFFERENCE THRESHOLD FOR MANUAL MASS discrimination. When these thresholds are compared with the difference thresholds for weight lifting, the threshold values are found to be FOUR TIMES AS LARGE AS THAT FOR WEIGHT. A comparison of the difference thresholds for weight lifting, manual mass discrimination and remote mass discrimination is presented above.

C. POSITIONING OF MASS

Other studies were carried out to determine man's ability to position objects with speed and accuracy in the absence of gravitational cues (ref. 4,5). Subjects moved objects of varying mass through several distances and directions on the frictionless table. Subjects were both fixed (standing) and tractionless (seated on the air-bearing scooter). Results showed that, for fixed subjects, object mass had no pronounced effect but changes in distance and direction led to significant changes in performance. Response time INCREASED while accuracy DECREASED with distance. Near-to-far movements were found to be FASTER BUT LESS ACCURATE than left-to-right movements.

For the tractionless subjects, mass produced significant differences in response time, heavier masses taking LONGER to position. In comparing the accuracy scores for both fixed and tractionless subjects, ACCURACY was found to be LESS for the tractionless group. RESPONSE TIMES, however, were SHORTER for the tractionless group.

IV. SUMMARY AND CONCLUSIONS

The report reviewed the results of analytical and empirical investigations of human motion capabilities in a gravity free environment. The results are intended to provide an overview of both the freedoms and the limitations characteristic of the surface-free operator.

The motion requirements of the operator were discussed in terms of a man performing maintenance and supply functions between, upon, and within space vehicles. A posture coordinate system was used as a basic reference and current studies concerned with rotating and translating the system were discussed. Study techniques included physical analyses of the motions, inflight validation of the analyses, and mathematical projections of probable orbital motions.

Within the limitations of the studies reported, several general concepts were generated and appear worthy of consideration in the assignment of tasks to the worker. The concept of MINIMUM MOTION FREEDOM suggests that the hazards of tumbling and collision be minimized by permitting the worker only the motion freedom required for task completion. Performance aids can be considered as being restraints in the form of safety lines, adhesive footgear, and rotation cancelling equipment. The force concept of CONSERVATION OF ENERGY OR TIME, normally an either-or choice, suggests that tradeoffs between the two can also be established in terms of motion requirements for task completion. HANDS-FREE OPERATION schemes presume that more tasks can be accomplished by the worker if his motion control does not require the use of his hands. POSTURAL CONTROL may be one method of accomplishing a hands-free operation whereby the direction of movement is directed by body adjustment. For example, a self-maneuvering unit could sense these adjustments and translate them into desired system motions. The idea of POSTURAL ORIENTATION implies that man may consider himself rather than his relationships to his surroundings as his main reference for attitude information. This concept could influence crew station layout (no floor-ceiling theme) and the display of attitude information (the moving element representing

the man rather than his surroundings). UNENCUMBERED MAN BASELINES (without hardware) of movement behavior are being established in order to define man's basic capabilities. The designer may then improve or limit motion performance by adding hardware to the man.

The first design consideration for developing the hardware should be the appreciation and USE of the unique weightless motions and sensations as they apply to task requirements. Restrictions and control of motions will be required, however, these limits are far outshadowed by the potential power of the weightless worker. With one impulse he can achieve unlimited motion (soaring) and given a stable platform (controlled rotation) he can handle tremendous amounts of materials. Free-floating man is indeed an intimate man-machine unit, a single vehicle-driver component capable of fantastic motion behavior.

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